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4 authors:

Zeki Bora Ön
Mugla Üniversitesi

Alan Greaves
University of Liverpool

Sena Akçer-Ön
Mugla Üniversitesi

M. Sinan Özeren
Istanbul Technical University

A Bayesian test for the 4.2 ka BP abrupt climatic change event in southeast Europe and southwest Asia using structural time series analysis of paleoclimate data*

Z. B. Ön†[1,2], A. M. Greaves[3], S. Akçer-Ön[1], and M. S. Özeren[2]

[1] *Muğla SK Üniversitesi, Mühendislik Fak., Jeoloji Böl., 48000, Muğla, Türkiye*
[2] *İTÜ, Avrasya Yer Bilimleri Enstitüsü, 34469, Ayazağa, İstanbul, Türkiye*
[3] *University of Liverpool, Dept. of Archaeology, Classics and Egyptology, Liv., UK*

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Abstract

It has been proposed that there was an abrupt climatic change event around 4.2 ka BP that affected societies and even has been linked to the collapse of empires. Subsequent studies have reached conclusions that both support and contradict the proposed event yet, nevertheless, 4.2 ka BP has now been adopted as the stratigraphic boundary point between the Middle and Upper Holocene. Time series plots of paleoclimate studies that claim to support the abrupt climate change hypothesis show differing temporal patterns so, in this study, we apply the Bayesian structural time series (BSTS) approach using the `CausalImpact` package to test data from southeast Europe and southwest Asia for which it is claimed that they demonstrate a climatic anomaly around 4.2 ka BP. To do this, each "affected" time series is synthetically reconstructed using "unaffected" series as predictors in a fully Bayesian framework by the BSTS method and then forecast beyond the assumed starting point of the event. A Bayesian hypothesis test is then applied to differences between each synthetic and real time series to test the impact of the event against the forecast data. While our results confirm that some studies cited in support of the 4.2 ka BP event hypothesis do indeed hold true, we also show that a number of other studies fail to demonstrate any credible effect. We observe spatial and data patterning in our results, and we speculate that this climatic deterioration may have been a consequence of an asymmetrical northward expansion or migration of the Northern Hemisphere Hadley cell. Furthermore, we observe that while the signals are generally not credible, types of proxy data from the Mesopotamia region and east are consistent with aeolian dust storms.

Keywords: Causal impact, Holocene, rapid climate change, Early Bronze Age, Eastern Mediterranean

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†Corresponding author: boraon@mu.edu.tr

1 Introduction

There were numerous rapid climate change (RCC) events in high latitudes of the Northern Hemisphere during the Late Pleistocene (Rasmussen et al., 2014). There have also been attempts to define RCC events similar to those seen in the Pleistocene for the Holocene, using available proxy data (Mayewski et al., 2004; Wanner et al., 2008). The possibility of RCC events in the Holocene is especially interesting given they would have taken place during a period of human history typified by complex human societies. RCC events can therefore serve as models for understanding the interaction between the natural environment and human cultures within the context of a rapidly changing climate.

One of the most controversial of the proposed RCC events is the so-called 4.2 ka BP[1] event, first proposed by Weiss et al. (1993). In their study Weiss et al. (1993) claim that, a major short-term climatic change between 4.2 and 3.9 ka BP contributed to the collapse of the Akkadian Empire. Following Weiss et al. (1993), further studies were published that appeared to confirm this hypothesis (see Weiss (2017) and Railsback et al. (2018) and references therein). In their initial article, Weiss et al. (1993) used aeolian deposits from archaeological contexts as well as excavated evidence and archaeological survey data to propose that increased regional aridity in the Habur Plains of Syria led to a decline in human settlement activity. Having begun as a drought phenomenon for the Upper Mesopotamia, mounting evidence from subsequent studies in other regions gradually led to the controversial (Bradley and Bakke, 2019b; Middleton, 2018; Ön et al., 2019; Voosen, 2018) acceptance of the 4.2 ka BP event as the geological stratigraphic boundary between the Middle and Upper Holocene (Walker et al., 2019).

There are, however, problems with some of the evidence for the 4.2 ka BP event, even that which is most widely cited (for a summary of the key evidences, see Walker et al., 2012; Weiss, 2015, 2017). For example, in different proxy data measurements taken from the same sample by Lemcke and Sturm (1997), the time series from quartz is one of the most widely used forms of evidence claimed as a proxy for aeolian activity for the 4.2 ka BP event by researchers other than the original authors (e.g. Walker et al. (2012) and Weiss (2017)), yet there is disagreement between that time series and any other time series (notably, relative humidity reconstruction) from the same sample, namely Van 90-10 sediment core of Lake Van. Asynchrony is also present for the same proxies in samples taken from adjacent, or identical, sampling sites. For example, a precipitation reconstruction by Kaniewski et al. (2013) at Tel Akko (Israel) shows a dry period around 4.2 ka BP, whereas a precipitation reconstruction during the same period from Dead Sea sediments reveals one of the wettest periods of the Holocene (Litt et al., 2012). Another important example is from the Mawmluh Cave (Meghalaya, India), because a previously studied speleothem sample from the same cave (Berkelhammer et al., 2013) now serves as the stratotype of the Meghalayan Stage (Walker et al., 2019). However, recently analyzed high resolution samples from the Mawmluh Cave (Kathayat et al., 2018) not only gave contradictory results about the timing of the 4.2 ka BP event, they also suggest that the intensity of the event was lower than that proposed by Berkelhammer et al. (2013).

[1] Kiloannum before present, meaning thousand years before 1950 CE.

Furthermore, while the timing of the event was originally postulated by Weiss et al. (1993) as being between 4.2 and 3.9 ka BP, some proxy data show a climatic event with significantly different start and end dates. For example, precipitation reconstruction from Tel Akko (Kaniewski et al., 2013) suggests a dry period starting at around 4.4 ka BP and the Soreq Cave geochemistry data (Bar-Matthews et al., 2003) show a drying trend starting at around 4.7 ka BP (Arz et al., 2015). It has therefore subsequently been claimed that the putative event may be a result of superimposed events starting before or around 4.7 ka BP (Drysdale et al., 2006; Kuzucuoğlu, 2007). Yet, on the other hand, there are also numerous examples of proxy data that do not show any abrupt change at all in the period around 4.2 ka BP (Andrews et al., 2020; Arz et al., 2015; Bradley and Bakke, 2019a; Göktürk et al., 2011; Jones et al., 2016; Ön et al., 2017).

The archaeological data is similarly complex and self-contradictory. For example, most major ancient settlements in the upper Euphrates basin and western Syria appear not to have been affected by any climate event, yet many settlements in the Khabur River basin were abandoned (cf. Kuzucuoğlu and Marro, 2007; Pfälzner, 2017; Schwartz, 2017), showing a regionally differentiated response to the event. The collapse of the Old Kingdom in Egypt appears not to have been abrupt, but rather a gradual de-urbanisation process that started several centuries before the 4.2 ka BP event (cf. Höflmayer (2015) and Moreno García (2015)). In the Levant, Anatolia and Italy archaeological sites were to show differing responses to the collapse of the Early Bronze Age state system and no single pattern can be discerned (see the articles in, Höflmayer, 2017a; Meller et al., 2015). We should not, therefore, expect to see a uniform response to the 4.2 ka BP event. When working with archaeological data we must always bear in mind the complexity of human societies and how they may respond differently to environmental change and not presume to predict their actions in a deterministic manner. Human agency means that different social groups can create different strategies to accommodate climatic change into their subsistence practices and societies. The nature of their pre-event agricultural strategies and social practices will also affect their ability to cope with changed environmental circumstances (Ur, 2015). Not only will these pre-event conditions influence a society's scope of action in response to climatic change, so too will the responses made by neighbouring communities. Collapse of one state can affect inter-connected communities in a domino effect for which climate may ultimately has been a contributory factor but to which different human communities will respond differently with changes to their own social organization, trade networks, or through war (Höflmayer, 2017b). Understanding this requires us to adopt an idiographic approach to human responses to change, as each society responds independently to the event, albeit within a context of inter-related social, commercial and military networks. As Ur (2015, p. 69) wrote: "only in rare circumstances does climate change force a uniform response from human communities". Human agricultural behaviors can change proxy data sets by, for example, shifting between arable and pastoralism—a change that would affect the near-environment of archaeological sites and become visible as aeolian deposits in the archaeological record. Only when independent proxy data indicate that there has been climate change should we begin to examine archaeological or historical data, or else we risk using unrelated human cultural dynamics as evidence of climate change. No archaeological or historical evidence for environmental change should therefore be considered to be a direct proxy for climate change, as it is always mediated by independent and unpredictable human actions (cf. Akçer-Ön et al., 2020; Haldon et al., 2020).

Our strategy in this study has been to synthetically reconstruct in a Bayesian manner every paleo-proxy time series for which it has been claimed that there is evidence of an abrupt change around 4.2 ka BP from southeast Europe and southwest Asia. Although new paleoclimate studies with high resolution data and robust age models will always be needed, there are now enough spatial/temporal data on which to begin building Bayesian models. While combining multiple time series and applying stochastic reconstruction within a large spatial scale and across spatially disparate data with age uncertainties is a challenging process, by testing the 4.2 ka BP hypothesis through a hierarchical Bayesian approach, it is possible to quantify the uncertainties of an impact[2] of a possible event reflected in the proxy data. By so doing, it is possible to plot a spatial distribution of any proven drought effect and hypothesize an underlying physical mechanism for its causation.

Reconstruction during the period prior to the putative 4.2 ka BP RCC event is handled by the BSTS method (Scott and Varian, 2014), which is mainly a linear regression model plus a trend component. BSTS is an effective way of constructing synthetic controls for time series data. The spike and slab regression component selects and weights the appropriate candidate controls, while the time series component captures temporal trends and serial correlation. If one assumes that there is a steady relation between the response variable and the BSTS model, then the forecast of the BSTS model can be used as a proxy for the response variable. In this study, time series from the same broad region that do not show any abrupt change during the period of interest are used as the control set (see, Fig. 1a, Table 1 and Fig. S1) and they are used as predictor variables in the regression model to reconstruct each response variable (see, Fig. 1b and Table 1) which are claimed to show the 4.2 ka BP event through a spike, wiggle or a similar geometric shape in time series of proxy data. The control set consists of time series that are assumed to describe the same dynamic process with the response variables, but must themselves not be affected by the impact, in either positive or negative direction. Furthermore, it is assumed that the underlying relation between the control set and the response variable, except for the impact itself, also continues to exist after the impact. Therefore, synthetic reconstructions of each response variable from the control set and a trend should not show any significant sign of the expected impact. According to the BSTS model, reconstructed time series are forecast from the point of impact by assuming a continuing dynamic relation between each response variable and each BSTS model. We infer the credibility of the impact of the conjectured climatic event on each proxy data, by finding the differences between the original and the posterior distribution of the predicted data during the temporal interval of interest. Consequently, we claim that the effect is credible (not credible) if the 95% posterior interval of the resulting semiparametric Bayesian distribution excludes (includes) zero.

Within this framework, the aim of this study is to generate synthetic time series of regional paleoclimate proxy data, for which it is claimed that they

[2]Within the scope of this study, the term "impact" signifies only a change in the nature of the time series. We do not presuppose the physical cause of that impact, which may be external or created by an extreme climate state as a result of nonlinear interactions within the dynamic climate system itself without any external trigger.

include evidence of an abrupt climate change around 4.2 ka BP and accordingly test the statistical credibility of that presumed abrupt change upon each of them.

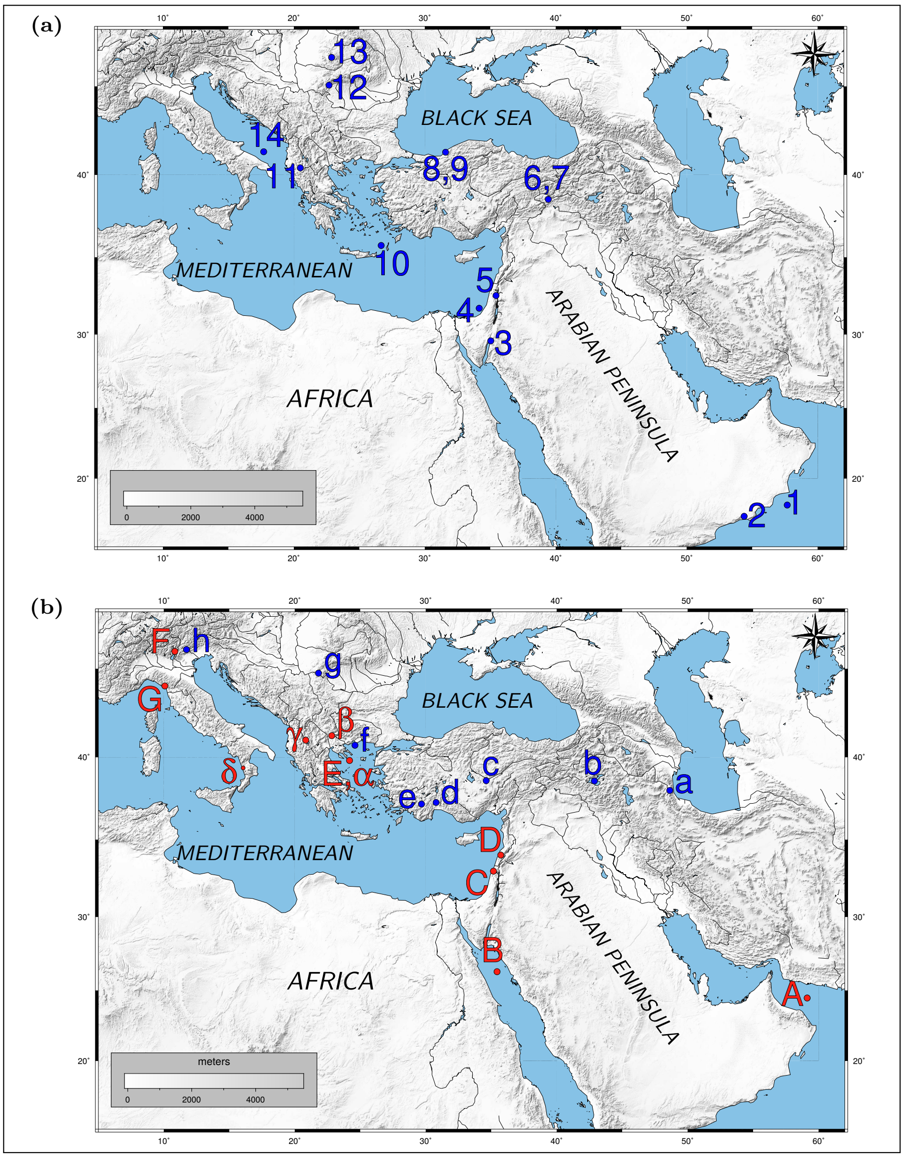

Fig. 1: Map of the broader region discussed in this study. (a) The locations of the control set variables shown with numbers. (b) The locations of the response variables. Red uppercase letters indicate the data confirming the hypothesis, whereas red Greek letters indicate the locations which confirm the hypothesis with an enduring level shift (for details, see Section 3). blue lowercase letters indicate the locations which do not confirm the hypothesis. For the references of the whole data, see Table 1. This map is prepared using GMT (Wessel et al., 2019) and ETOPO1 relief model (Amante and Eakins, 2009).

2 Materials and methods

2.1 Data

Since, no recorded climate data exist for the specified time period, if we are to apply a test to the validity or spatial distribution of the 4.2 ka BP event, we must rely on various types of noisy paleoclimate proxy data time series from different environmental contexts. Paleoclimate proxies are assumed to be noisy indicators of regional and to some extent large-scale environmental changes. Their climatic interpretation is not straightforward and requires "careful calibration and cross-validation procedures" (Folland et al., 2001, p. 130). We therefore leave the environmental interpretations of data to the original authors of the selected studies. Different proxy types exist, and they differ in output data and noise levels (for an extensive review see, Bradley, 2015). Ideally, we would discuss this problem using same type of proxy data sets from the case study region. However, the whole available data according to the selection criteria explained in the next paragraph, are given in Table 1 and even this selection leaves us spatially scarce (Fig. 1) and different types of proxy data from a wide geographical region.

The longer the data sequences used to reconstruct a targeted time series (response variable) by BSTS, the more robust it will be and the application of BSTS is only possible if the control set contains no missing values. With this in mind, it is important to note that there is another suggested climate event similar to the 4.2 ka BP event, at around 8.2 ka BP (see Walker et al., 2012), which we have excluded from our analysis. We therefore selected paleoclimate proxy time series for the control set from the broader region using two criteria: that they have to span the period between 7.45 and 2.7 ka BP and that the original data should have an approximate temporal resolution of at least 50 years. The boundary points of the interval, i.e. specifically 7.45 ka BP and 2.7 ka BP, were selected so as to take advantage of almost continuous GeoB5804-4 (Lamy et al., 2006) and Qunf Cave (Fleitmann et al., 2007) data to be included in the control set. It would also have been possible to select 3.9 ka BP as an end point but defining a longer period allows us to show the forecasting capability of the method, at least for some response variables. Applying these criteria, we chose the interval from 4.4 ka BP to 2.7 ka BP, a total forecasting period of 1700 years. The selection of 4.4 ka BP as the start point of the event avoids the possible creation of bias from age models and to include the apparent event in the data of Drysdale et al. (2006) (see Section 3 for the discussion).

The BSTS method (see Section 2.2 and supplementary material) requires evenly spaced data and predictors and responses must be observed at the same set of discrete time points. Since none of the time series data used in this study (Table 1) are synchronous, all of them are linearly interpolated to 50 years resolution between 7.45 and 2.7 ka BP. For a description of the pre-processing, see supplementary material.

Table 1: Paleoclimate proxy data used in this study. The data given in the upper panel are the response variables that it is claimed to show an abrupt change during the period of interest, in the context of causal impact method. The letters are given according to the results gathered in this study: upper case Latin letters confirm the abrupt change hypothesis; lower case Greek letters indicate a change at the period of interest with a level shift; lower case Latin letters give no statistically valid change (for details, see Section 3). The lower panel shows the control set in the context of causal impact method, which do not show a change during the period of interest. Site type and other used abbreviations are as follows: M=Marine, AS=Archaeological site, S=Speleothem, L=Lake, I=Ice core, SST=Sea surface temperature TSAR=Terrigenous sand accumulation rate.

Location (Sample name)	Site type	Proxy	Proxy interpretation	Reference
1. Arabian Sea (RC27-23)	M	$\delta^{15}N$	Denitrification	Altabet et al. (2002)
2. Qunf Cave (Q5)	S	$\delta^{18}O$	Precipitation	Fleitmann et al. (2007)
3. Gulf of Aqaba (GeoB 5804-4)	M	TSAR	Aeolian depos.	Lamy et al. (2006)
4. Eastern Med. (GeoB 7702-3)	M	TEX_{86}	SST	Castañeda et al. (2010)
5. Lake Kinneret (KI_10_I,II)	M	diatom	Lake level	Vossel et al. (2018)
6. Lake Hazar (Hz11-P03)	L	Hz-ic4	Precipitation	Ön et al. (2017)
7. Lake Hazar (Hz11-P03)	L	Hz-ic5	Temperature	Ön et al. (2017)
8. Sofular Cave (So-1)	S	$\delta^{13}C$	Effective moist.	Göktürk et al. (2011)
9. Sofular Cave (So-1)	S	$\delta^{18}O$	Moist. source	Göktürk et al. (2011)
10. Aegean Sea (LC21)	M	warm sp.(%)	SST	Rohling et al. (2002)
11. Lake Maliq (K6)	L	pollen	Precipitation	Bordon et al. (2009)
12. Ascunsa Cave (POM2)	S	$\delta^{18}O$	Temperature	Drăguşin et al. (2014)
13. Scărişoara Cave (SIC)	S	$\delta^{18}O$	Temperature	Perșoiu et al. (2017)
14. Adriatic Sea (MD90-917)	M	foram.	SST	Siani et al. (2013)
A. Gulf of Oman (M5-422)	M	$CaCO_3$	Aeolian depos.	Cullen et al. (2000)
B. Red Sea (GeoB 5836-2)	M	$\delta^{18}O$	SSS	Arz et al. (2006)
C. Tel Akko (Akko core)	AS	pollen	Precipitation	Kaniewski et al. (2013)
D. Jeita Cave (J-1)	S	$\delta^{18}O$	Precipitation	Cheng et al. (2015)
E. Aegean Sea (GeoTü SL148)	M	smect./ill.	Drought	Ehrmann et al. (2007)
F. Lake Ledro (LL081)	L	pollen	Summer precip.	Peyron et al. (2013)
G. Buca della Renella (RL4)	S	$\delta^{18}O$	Precipitation	Drysdale et al. (2006)
α. Aegean Sea (GeoTü SL148)	M	$\delta^{13}C_{Um}$	Productivity	Kuhnt et al. (2008)
β. Lake Dojran (Co1260)	L	$CaCO_3$	Productivity	Francke et al. (2013)
γ. Lake Ohrid (Lz1120)	L	$CaCO_3$	Productivity	Wagner et al. (2009)
δ. Lake Trifoglietti (S2)	L	pollen	Summer precip.	Peyron et al. (2013)
a. Neor Lake	L	XRF-Ti	Aeolian depos.	Sharifi et al. (2015)
b. Lake Van (Van 90-10)	L	quartz	Aeolian depos.	Lemcke and Sturm (1997)
c. Eski Acıgöl (ESK96-97)	L	$\delta^{18}O$	Water balance	Roberts et al. (2001)
d. Kocain Cave (Ko-1)	S	$\delta^{13}C$	Winter temp.	Göktürk (2011)
e. Gölhisar (GHA)	L	$\delta^{18}O$	Water balance	Eastwood et al. (2007)
f. Skala Marion Cave (MAR_L)	S	$\delta^{18}O$	Precipitation	Psomiadis et al. (2018)
g. Poleva Cave (PP98-10)	S	$\delta^{18}O$	Temperature	Constantin et al. (2007)
h. Grotta di Ernesto (ER76)	S	$\delta^{13}C$	Temperature	Scholz et al. (2012)

2.2 Causal impact

Through BSTS each response variable is defined in a structural time series model (Scott and Varian, 2014, 2015). The main component of the model for this study is linear regression. Other components, such as trend, seasonality or autoregression can be defined modularly in structural time series models (see Durbin and Koopman, 2012). The basic structural time series model used in this study is defined through the following set of equations:

$$\begin{aligned} y_{t+1} &= \mu_{t+1} + \beta^{\mathsf{T}} \mathbf{x_{t+1}} + \epsilon_{t+1}, \\ \mu_{t+1} &= \mu_t + \delta_t + \xi_t, \\ \delta_{t+1} &= \delta_t + \zeta_t. \end{aligned} \tag{1}$$

At Eq. (1), y_t is the observed data at time t (in this study, any of the time series at the lower panel of Table 1), which in our case is proposed to show an abrupt change around 4.2 ka BP. The model includes a local linear trend μ_t and a linear regression component with $\beta^T \mathbf{x_t}$. Linear trend is defined via a dynamic slope δ_t which is a random walk. $\mathbf{x_t}$ is the $K \times 1$ vector of contemporaneous covariates (in this study, vector of data points at time t for the control set shown at the upper panel of Table 1) and β is the $K \times 1$ regression coefficients vector associated with the control set. At Eq. (1), ϵ_t, ξ_t and ζ_t are statistically independent and normally distributed error terms with zero mean. Parameters of the model are variances of the error terms and β, regression coefficients. Regression coefficients are selected in a hierarchical fashion within the model via Gibbs sampling, through a method called *stochastic search variable selection* (George and McCulloch, 1993). For details of the synthetic reconstruction of each response variable through Bayesian estimation, cross validation procedure for parameter selection and evaluation of the impact on response data, see the supplementary material and references therein.

All the computations are made using the open source `CausalImpact` package (Brodersen et al., 2015) under a free and open source statistical software R (R Core Team, 2019).

3 Results and discussion

Our results are summarized in Fig. 1 and Table 1. Detailed explanation of the methods by which these results were achieved can be found in the supplementary material. These results are based on reconstructions of response variables via the control set on a broad geographical area and calculation of the credibility of the impact across a specific interval. Decisions and assumptions made about these processes and variables will affect the results. Therefore, we present our discussion on these decisions and assumptions before the results.

Our method is to perform a BSTS fit to each data set for which it has been claimed that they show an abrupt event around 4.2 ka BP and check the credibility of an effect of a possible climatic event on the response variables. The selected control set (Table 1, upper panel) is composed of time series from the same wide region, which show no abrupt change, in either positive or negative directions, during the 4.4 to 3.9 ka BP interval. For this article we use all data, including age models, as presented in the original publications. All these data come from different studies, which may themselves include certain biases in terms of their own age models/uncertainties, laboratory measurements, and the specific nature of different proxy data. However, the use of multiple time series with Bayesian stochastic averaging is one of the most robust, holistic and state-of-the-art approaches in the presence of such uncertainties.

Unlike instrumental climate data, in paleoclimate science, proxy data are dependent upon many different processes (cf. Ön and Özeren, 2018; Roberts et al., 2008). Furthermore, they are scarce and may have relatively low resolution. Some of them may contain hiatuses, sections of the record needed to make the desired measurement may be unavailable or the outputs of the analyses may not give quantitative results. Therefore, in order to achieve the desired analysis, we selected all available data within the region that meet *almost* all the conditions described in Section 2.1. Within this constrained picture, selection of the data mainly depends on the assumption of dynamic atmospheric connection across the extended region and therefore it is assumed that a relation between the proxy variables should exist. This assumed *weak* connection is verified by analogy to the Late Pleistocene millennial scale RCC events in the same region (e.g., Çağatay et al., 2014; Fleitmann et al., 2009; Torfstein et al., 2013; Wegwerth et al., 2015). In some studies, chronologies are even constructed on the basis of this assumption (e.g., Stockhecke et al., 2016; Zanchetta et al., 2016). The whole region is also, to some extent, affected by multiple hemispheric pressure gradients and circulation patterns (Bozkurt et al., 2012; Cullen and deMenocal, 2000; Roberts et al., 2012; Ulbrich et al., 2012) and therefore, we assume that all the data in this study can be assumed to have dynamic interrelations throughout the analyzed period. With this assumption about the data, the spike and slab prior variable selection technique is assumed to select the most statistically appropriate predictor variables from the control set for each response variable (George and McCulloch, 1997; Scott and Varian, 2014).

According to the original hypothesis proposed by Weiss et al. (1993), the onset of the drought event in Tell Leilan was around 4.2 ka BP and it ended at around 3.9 ka BP. Subsequent studies have since enlarged the length of this interval. For example, Drysdale et al. (2006) have suggested that the event took place between 4.4 and 3.8 ka BP and, in a recent study, Zanchetta et al. (2018) bounded the interval of a possible event for the central Mediterranean between 4.4 and 3.9 ka BP. The stochastic model used to construct response variables in this study has two components, local linear trend and regression (see Section 2.2). The causal impact method applies a test to the differences between the response variable and the synthetically reconstructed time series during the period of interest. Had we restricted the onset of the event to 4.2 ka BP, this might have generated misleading results for some data series because, if the event starts before 4.2 ka BP in a data set, the trend and/or the regression component would adapt themselves to the existing level, which is clearly different from the *normal* conditions in the time series. A good example of this situation is the adaptation of the red dashed lines to Neor Lake Ti count data (Sharifi et al., 2015) between 6.4 and 4.8 ka BP (see Fig. 2). Therefore, if the test were applied to all time series from 4.2 ka BP onwards only, then the results from time series such as Buca della Renella $\delta^{18}O$ (Drysdale et al., 2006) may have been misleading. Therefore, for all the time series in this study, following Zanchetta et al. (2018), we assumed that the onset of the climatic event was 4.4 ka BP and it ended at 3.9 ka BP.

The proposed impact has different influences on the appearance of the time series (see, Fig. 2). In some of them, the general trend of the time series returns to its pre-impact levels after the cessation of the impact interval, while in the other cases we don't observe any such resilience and the signals experience an enduring level shift (often negative) that lasts longer than the hypothesized impact interval (see discussion below). While the cause of this shift may be explained by a possible deforestation due to human intervention in Lake Dojran

(Francke et al., 2013), we can find no explanation for it in other studies. For the rest of the records, the event may have caused an *enduring* effect due to the impact on the specific element of the environment from which the proxies were sampled. An example of paleoceanographic changes would be that an extended drought may impose a significant change in the oceanic convective overturning regime that, in turn, permanently changes the residence time of $\delta^{13}C$ (Kuhnt et al., 2008) leading to a level shift in the time series after the cessation of the impact period. Further terrestrial examples of how a period of aridity may cause an enduring change in the flora or sedimentary character of a watershed due to natural and/or anthropogenic causes may be the pollen record from Lake Trifoglietti (Peyron et al., 2013) and geochemistry record form Lake Ohrid (Francke et al., 2013). These may be good examples of a shift from one stable state to another stable state which can be explained by multiple equilibria within a dynamical climate system.

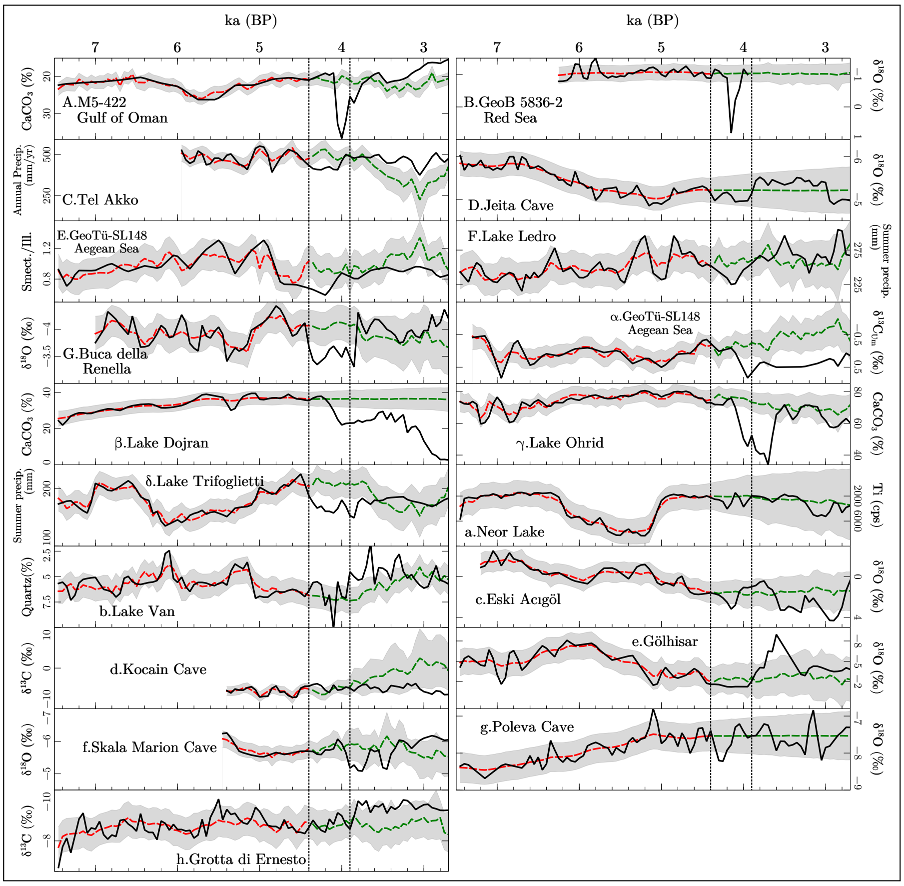

Fig. 2: Causal impact analyses for the response variables given in Table 1. Black lines show the original time series, interpolated to 50 years resolution, as explained in Section 2.1. Red dashed lines show the reconstructed time series for the pre-period and green dashed lines show the forecast for the post-period, respectively. Gray clouds in each plot indicate the 95% credible intervals. Dashed vertical lines mark the interval between 4.4 and 3.9 ka BP, where the validity of the effect of an impact is checked. All the graphs are plotted to represent the effect in the negative direction.

In our results three different behaviors can be discerned in the time series following the onset of the presumed impact. The first group consists of seven time series (shown as uppercase letters in Fig. 1b and Fig. 2, including Cullen et al. 2000; Arz et al. 2006; Drysdale et al. 2006; Ehrmann et al. 2007; Kaniewski et al. 2013; Peyron et al. 2013-Lake Ledro; Cheng et al. 2015) that confirm the hypothesis of Weiss et al. (1993) in that they not only coincide with the suggested onset date but also have approximately the same duration as that proposed by Weiss et al. (1993), or more correctly the revised date and duration proposed by Zanchetta et al. (2018). The second proxy group consists of four time series (shown as lowercase Greek letters in Fig. 1b and Fig. 2, including Kuhnt et al. 2008; Wagner et al. 2009; Francke et al. 2013; Peyron et al. 2013-Lake Trifoglietti) and display an impact in the time series but with an enduring level shift after cessation of the proposed impact period.

The third group consists of eight time series (shown as lowercase letters in Fig. 1b and Fig. 2, including Lemcke and Sturm 1997; Roberts et al. 2001; Constantin et al. 2007; Eastwood et al. 2007; Göktürk 2011; Scholz et al. 2012; Sharifi et al. 2015; Psomiadis et al. 2018) and, according to the test against the reconstruction, indicate no abrupt change during the period of interest. That is to say, in these eight cases the time series continue to fluctuate within predicted parameters of stochastic credible intervals and the effect of the impact, if any, is negligible.

However, we should comment here on some important points of note. Lack of an impact does not mean the tested proxy data show no event. According to the test, the result is statistically not credible, which is not the same as non-existent. For example, there is a clear local maxima of quartz content of Lake Van (Lemcke and Sturm, 1997) at around 4.1 ka BP but its temporal length does not span the entire hypothesized period and, rather, it covers only a relatively short period. Since our model tests the credibility of the differences between original and reconstructed series from 4.4 through to 3.9 ka BP, the Lake Van result appears as the conjectured impact having no credible effect on the time series. While this may seem problematic, the physical reason for such a short term transient event will be discussed in subsequent paragraphs. Secondly, the reverse circumstance is also possible. For example, the event in the $\delta^{18}O$ record from the Jeita Cave (Cheng et al., 2015) is weaker than the events observed between 5.2 and 4.9 ka BP and after 3 ka BP in the same record. However, the cumulative effect found by the summation of the differences between the original and reconstructed data through the period of interest leaves us with a "barely" credible effect (see Fig. S23). Besides, changing the k value, which is a hyperparameter describing the weights of regression and trend found through cross-validation (see supplementary material), may change the result of the test on the Jeita Cave data (since Bayesian one-sided tail-area probability of the result is too close to 0.05 and which can be seen in Fig. S23). However, a change in the result of a single series would not change our results. Thirdly, temporal lengths from the Kocain Cave (Göktürk, 2011), Skala Marion Cave (Psomiadis et al., 2018) and, to some extent, Tel Akko (Kaniewski et al., 2013) data are substantially shorter than the rest of the response variables, a condition which reduces the confidence of the analyses for these sites. Lastly, the Skala Marion Cave experienced a drought between 3.9 and 3.7 ka BP, yet this was put forward as further evidence for the 4.2 ka BP event by Psomiadis et al. (2018). Since our hypothesis testing is applied strictly to the interval between 4.4 and 3.9 ka BP, this period is not taken into account by our analysis.

Initial consideration of our results may at first appear to suggest that the locations where the proposed impact has been demonstrated do not form any coherent geographical patterning or regional cluster because they are spatially diffuse across the study region. For example, we detected the impact in Buca della Renella in Italy (Drysdale et al., 2006) to the west and in the Gulf of Oman (Cullen et al., 2000) to the east, which are two of the most extreme diametrically opposed locations within the region.

However, on closer inspection it is possible to discern a potential spatial distribution trend that does not follow a simple longitudinal or latitudinal division, but rather curves across the study region along a southeast-northwest line. Almost all the locations showing a drought during the 4.2 ka BP event lie roughly south of this hypothetical line (Fig. 3). A similar north-south patterning has been observed in pollen data from the Italian Peninsula (Di Rita and Magri, 2019) and also for the Mediterranean region as a whole (Magny et al., 2013), but our results do not indicate quite such a strict north-south division.

The precipitation regime of the region shows a very high seasonality (see, Fig. S24) and this is mainly due to the latitudinal migration of the Intertropical Convergence Zone (ITCZ) and, accordingly, the subtropical high pressure belt (STHP) over northern Africa. In winter, the region receives precipitation mainly through westerlies but, in summer it is dry. The southeast-northwest spatial pattern offered in the previous paragraph may be due to asymmetrical bending or expansion of the STHP affecting precipitation during the winter months. Possible explanations to this phenomena might be an asymmetrical migration of the ITCZ, or an asymmetrical expansion of the Northern Hemisphere Hadley cell. If it were an asymmetrical migration of the ITCZ, then in Northern Hemisphere winter one would expect it to be wetter in the south African savanna (see, Fig. S22). However, reported data (Chase et al., 2009; Railsback et al., 2018, green squares at Fig. 3) from south Africa suggest that the region was experiencing wetter conditions at this time. An asymmetrical expansion of the Hadley cells to the north in the Northern Hemisphere and to the south in the Southern Hemisphere would result in a drought over the Mediterranean and may, in turn, result in more humid conditions, over the western parts of north and south African savanna. To confirm such a hypothesis, it would be desirable to gather more paleoclimate data from different sides of the spatial transect identified in this study and also to collect more African subtropical paleoclimate data, similar to those presented by Chase et al. (2009) and Railsback et al. (2018) which propose a wetter phase during our temporal period of interest (see, Fig. 3).

Furthermore, unlike the rest of our study region, the evidence from the Middle East cited as evidence of drought is mainly in the form of proxies of increased aeolian deposits (see, Fig. 3) including quartz (%) in Lake Van (Lemcke and Sturm, 1997), $CaCO_3$ (%) in the Gulf of Oman (Cullen et al., 2000), XRF-Ti count in Neor Lake (Sharifi et al., 2015), Mg/Ca ratio in Gol-e Zard (Carolin et al., 2019) and even the aeolian deposits of Tell Leilan presented by Weiss et al. (1993). However, other available proxies included in these same studies, such as stable isotopes, generally do not show any drought pattern. This increased aeolian deposition may be due to increased aridity in the central and eastern Mediterranean through the mechanism proposed in the previous paragraph and correspondingly stronger westerlies that may have increased the volume or strength of dust transportation to the Middle East.

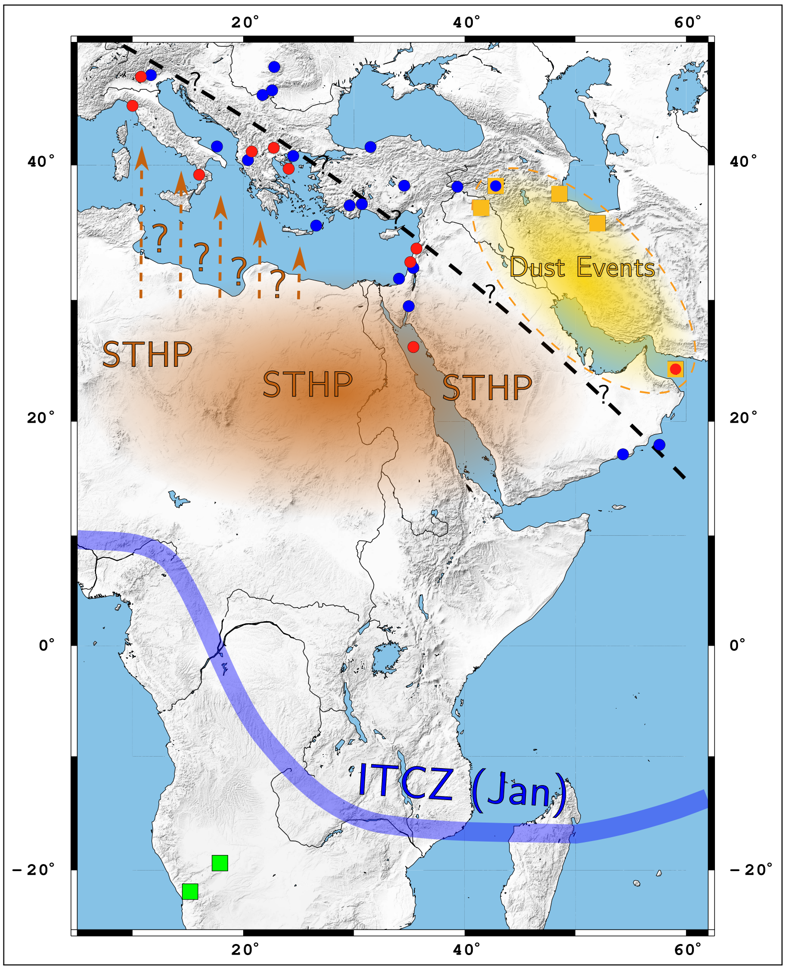

Fig. 3: The map shows a speculative line (dashed black line) dividing the studied region from northwest to southeast and a hypothesized cause showing the asymmetrical migration or expansion of the STHP. Red/blue dots indicate locations showing/not showing a drought during the 4.2 ka BP event. The yellow ellipse covers proxy data showing aeolian activity and the yellow squares show the locations of aeolian activity proxy (Carolin et al., 2019; Cullen et al., 2000; Lemcke and Sturm, 1997; Sharifi et al., 2015; Weiss et al., 1993) that are mentioned in the main text. The green squares over Africa indicate the locations of the data (Chase et al., 2009; Railsback et al., 2018) which show a wetter period during the period of interest. The January location of the ITCZ is plotted after Yan (2005). This map is prepared using GMT (Wessel et al., 2019) and ETOPO1 relief model (Amante and Eakins, 2009).

A possible candidate that might account for such a climate phenomenon, and cited in some of previous studies, would be a shift in the El Niño-Southern oscillation (Haug et al., 2001; Sirocko, 2015; Staubwasser and Weiss, 2006). Therefore, the drought which has been observed asymmetrically in our study region of southeast Europe and southwest Asia may find its origins in an event in or around the Indo-Pacific Ocean, and this possibility should be investigated in further studies.

4 Conclusions

Paleoclimate proxy time series that have previously been claimed to show evidence of the 4.2 ka BP abrupt climatic event have been synthetically reconstructed in this article within a fully Bayesian framework, based on the BSTS method with trend and regression components. Using this, the model is forecast for the 4.4 to 3.9 ka BP interval and the credibility of any possible effect is inferred from the difference between the projected forecast and the observed results. Three structural groups can be identified within the results of our analysis and the results can be summarized as below.

1. Data that show the proposed 4.2 ka BP event are from the Gulf of Oman (Cullen et al., 2000), the Red Sea (Arz et al., 2006), Tel Akko (Kaniewski et al., 2013), Jeita Cave (Cheng et al., 2015), north Aegean Sea-Smectite/Illite (Ehrmann et al., 2007), Lake Ledro (Peyron et al., 2013) and Buca della Renella (Drysdale et al., 2006).

2. Data that show an event during the 4.2 ka BP period of interest but with an enduring level shift in the time series thereafter. This is observed in data from the north Aegean Sea-$\delta^{13}C_{Um}$ (Kuhnt et al., 2008), Lake Dojran (Francke et al., 2013), Lake Ohrid (Wagner et al., 2009) and Lake Trifoglietti (Peyron et al., 2013). Why a period of aridity should cause such an enduring change in climate proxy data is as yet unclear. Possible explanations may include landscape evolution, such as deforestation that affected human occupation strategies (or was or affected by a human response to environmental pressures caused by prolonged drought), or are due to the dynamical character of the proxy data itself. This question will be the subject of future studies by the authors.

3. The third group of proxy data do not show any change that can be described as an abrupt effect, including those from Neor Lake (Sharifi et al., 2015), Lake Van (Lemcke and Sturm, 1997), Eski Acıgöl (Roberts et al., 2001), Kocain Cave (Göktürk, 2011), Gölhisar (Eastwood et al., 2007), Skala Marion Cave (Psomiadis et al., 2018), Poleva Cave (Constantin et al., 2007) and Grotta di Ernesto (Scholz et al., 2012). The fluctuations of these time series around the period of interest are acceptable within stochastic credible intervals.

4. The geographic distribution of our results presented here is suggestive of a drought mainly concentrated in the southwestern half of our study region. We speculate that asymmetrical northward expansion or migration of the high pressure system over North Africa may have been a potential mechanism governing this kind of a spatial pattern.

5. All available evidence in and around Mesopotamia are aeolian deposit proxies. This would be consistent with a drought in the central Mediterranean and the Levant, represented in proxy data as increased dust storms in the semiarid region of Mesopotamia and the Zagros Mountains to the east and north.

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Code availability All the data used through this study and the code are available through https://github.com/zboraon/causalimpactfor4_2kaBPevent.

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